The Water Supply System of Ancient Pompeii (Southern Italy): From Resource to Geohazard

Maria Rosaria Senatore, Maddalena Falco and Agostino Meo

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http://dx.doi.org/10.5772/64413

Abstract

Pompeii, a famous ancient city in the southern Italy, was finally demised by the Plinian eruption in the 79 AD, but, long before it was hit by two alluvial mass flows that damaged the city. These pre-79 AD volcaniclastic deposits had been emplaced by avalanches, slumps, and associated debris flows (secondary lahars) during volcanically quiescent phases of the Somma-Vesuvius volcano. These deposits were transported and channelized along stream beds. Some of these extended to the immediate proximity of Capua Gate, at the northern side of Pompeii, where an artificial canal was built to supply water to the city. The canal path continues toward Vesuvius Gate and then, toward Villa of Mysteries. The flood deposits were released from hyperconcentrated slumps and debris flows. The first flood event, not transported through the artificial canal, took place before the foundation of the city (764 BC) and has affected a wide area of the Sarno Plain. The second one, occurred during the fourth century BC, was caused by the canal's limited width and produced severe damage in the archaic city. Instead, the third flood event occurred in 170 BC and caused severe damage in the northern part of the city. The geological data prove that the water, as resource, in some cases can turn into a geohazard.

Keywords: geological stratigraphy, sedimentology, water supply, artificial canal, flood event, ancient Pompeii

1. Introduction

Pompeii, a famous ancient city in the Southern Italy, is located southeast of Naples in the Sarno Plain at the base of the Somma-Vesuvius volcano and about 2 km from the present Tyrrhenian coastline (**Figure 1**). The Sarno Plain is part of the Campania Plain, a wide Plio-Pleistocene tectonically depressed area (graben) bounded by Mesozoic and Cenozoic carbonate mountains. The graben is partially filled by alluvial, transitional, and marine deposits that are interbedded with pyroclastic deposits mainly from the eruption of the Somma-Vesuvius [1]. The geography and the development of land and population of the Campania Plain have all been conditioned by the volcanic activity [2–4]. The Late Pleistocene and Holocene volcanic activity of the Somma-Vesuvius is characterized by catastrophic Plinian and sub-Plinian eruptions, followed by inter-Plinian and quiescence phases [5–8]. During the settlement of Pompeii, the volcanic activity was weak or absent and the population ignored how danger was the area.

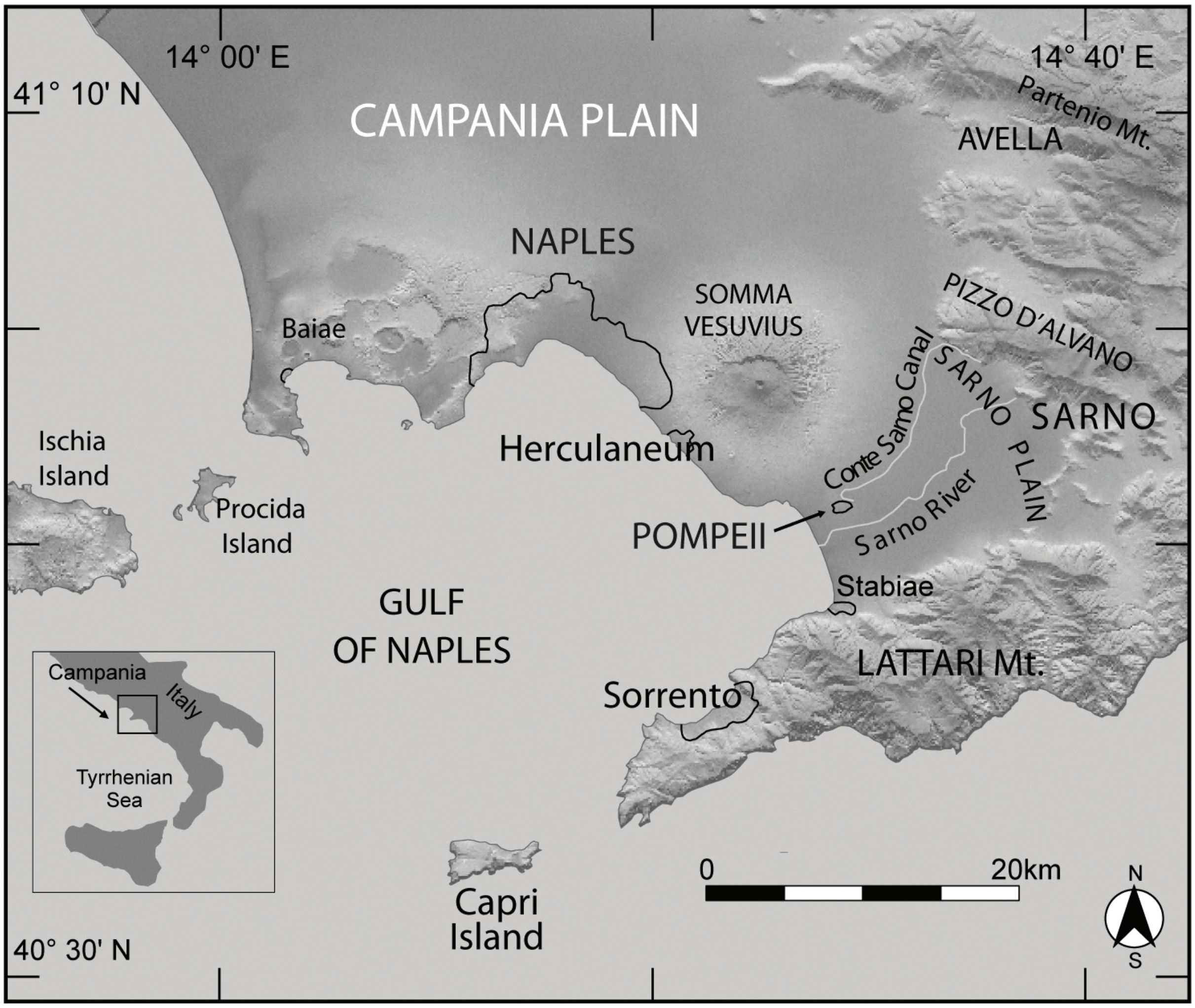

Figure 1. Location map of the Campania Plain – Gulf of Naples. Pompeii, other population centers, and geographic features are showed.

Pompeii was founded at the end of the seventh century BC by the Oscans, a population from central Italy [9, 10]. The town was built on a lava flow or on a separate volcano [11] associated with eruptive events of the Somma-Vesuvius.

Long before its major destruction by the well-documented earthquake in 62 AD [12, 13], and its final demise from the Plinian eruption in 79 AD (called the Pompeii eruption; e.g., [14–17]), Pompeii was damaged by two alluvial mass flows [18, 19]. These pre-79 AD volcaniclastic deposits had been emplaced by avalanches, slumps, and associated debris flows (secondary lahars) during volcanically quiescent phases of the Somma-Vesuvius volcano [20]. These deposits were transported and channelized along stream beds, some of which, extended to the immediate proximity of the northern wall of the city. Nowadays, there are no obvious rivers that would indicate how gravity flows would have reached into the walled city, but there is a stream, named Conte Sarno Canal, extending from the base of the Pizzo D'Alvano Mount (1133 m elevation; **Figure 1**) about 15 km to the northeast from Pompeii. On the northeastern side of the city, the stream shows a large bend (meander) due to the sudden change of the topographic relief occurred as a result of the barrier caused by the lava mound upon which Pompeii was built. The stream originally flowed from the Avella Mountains (**Figure 1**) and, during the Samnite occupation of the city (V–IV century BC), was associated with springs located at the base of the Pizzo D'Alvano ridge [21]. Borehole data collected northwest of the city indicate that a fluvial system reached Pompeii outside of Capua Gate (**Figure 2**). According to [18], the fluvial system was an artificial branch of the Conte Sarno Canal that was diverted

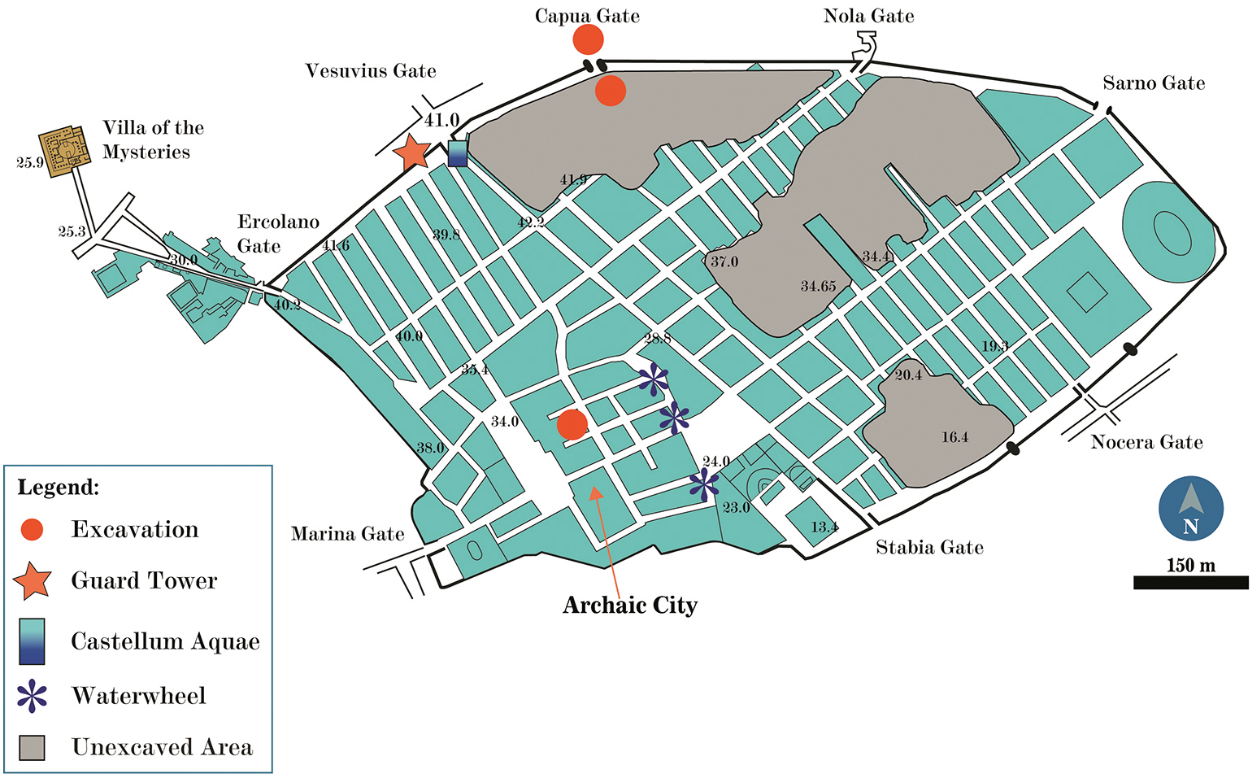

Figure 2. Archaeological area of Pompeii. The archaic part of the city and other archaeological features are showed and the position of archaeological excavations and of unexcavated areas is located. The numbers correspond to the topographic elevation.

toward west and had most likely been excavated to supply the city with water. It was constructed by Samnites as evidenced from the modifications performed along the path of Conte Sarno Canal discovered by [21].

This chapter has two aims: the first is to show the characteristics and the path of the artificial canal discovered to the north of Pompeii, which provided water to the city; the second is to detail the flood units by new borehole data carried out in the south of the ancient city.

Previously the historians studying Pompeii have long suggested that the city's water needs were derived from the Sarnus River (modern Sarno River; **Figure 1**), the largest fluvial system in the area [22–24]. However, nowadays, the modern Sarno channel is positioned to the southeast and south of Pompeii, and the meandering course of the ancient Sarnus River and its delta, identified by analysis of the sediment collected in boreholes, was located at least 1 km south and southwest of the ancient city walls [18, 24–29]. Moreover, the elevation pattern within the city shows that Capua and Vesuvius gates are both positioned at highest elevations (**Figure 2**). Therefore, they occupy strategic points for distribution of the city's water supply. It was from here that water of the artificial canal, entering into the city, discharged by gravity, was able to activate three water wheels (**Figure 2**) located at the edge of the archaic city [30, 31]. However, this artificial canal was also very dangerous because it had been the cause of two of three floods that led to extensive damage to the city. In fact, Senatore et al. [18] have identified, both within the city and outside it, three units referred to debris-flow deposits dated between the eighth and the second century BC. These mass flows are interpreted as having been triggered primarily by intense rains and channelized via the stream that once extended from high reliefs toward Pompeii and, then, through the artificial canal that reached the city. According to these authors, one of these events may have been partially responsible for urban decline during the fourth century BC. New data on the characteristics and distribution of the alluvial deposits related to the two more recent flood events will be analyzed. The interpretation of geological data will prove that a resource, the water, in some cases can turn out to be a geohazard.

2. Water supply system and flood events

2.1. Method

The aim of the researches, carried out in the Pompeii territory since 1995, has been the reconstruction of the paleo-landscape prior to the AD 79 Vesuvius eruption by means of geological stratigraphy and facies analysis. As the studied area is strongly urbanized, about 100 continuous drill-cores were carried out. The detailed stratigraphy of sediments in these drill-cores has been the base reference to re-interpret about 400 logs of older drill-cores. In this chapter, the results of analyses of several boreholes recovered to the northwest (C in **Figure 3**), south, and inside of the city (F in **Figure 3**) are detailed.

Several archeological excavations in the city were analyzed (**Figure 2** and S in **Figure 3**). An electrical resistivity tomography (ERT) profile (TM1 in **Table 1** and **Figure 3**) was recorded on the unexcavated front of a dig carried outside of Capua Gate (**Figure 2**) made by the Japan Institute of Paleontological Studies of Kyoto [32]. The dig brought to light an artificial canal and the TM1 ERT profile analyzed by [18] was made to obtain additional information on the subsurface stratigraphic architecture.

Since 2013, four more ERT profiles were carried out (**Table 1** and **Figure 3**) to reconstruct the path of the artificial canal. The equipment included an MAE A3000E Georesistimeter. The electrical-resistivity measurements recorded were processed through the inversion software RES2DINV by GEOTOMO INTERNATIONAL. The Wenner-Schlumberger and dipole-dipole-array methods were employed as a measure of resistance distribution; Res3DInv software was used for data interpretation. Additional information on the geoelectric equipment and settings used are available in two internal reports [33, 34].

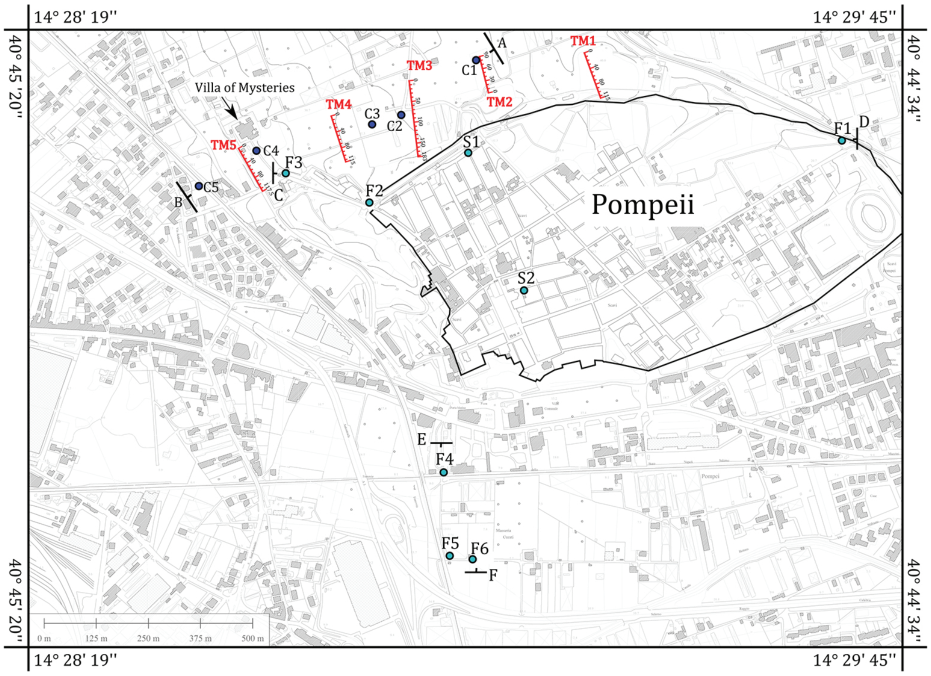

Figure 3. Position of: (C) boreholes passing through the channel units; (F) boreholes passing through flood units; (S) excavations in the city; and (TM) electrical resistivity tomography (ERT) profiles. Section traces are also indicated.

Tomography	Interelectrode spacing	Electrode number	Profile length	Trending	Maximum depth reached
TM1	5.0 m	24	115 m	N 350° E	20.0 m
TM2	1.9 m	48	89.3 m	N 344° E	17.0 m
TM3	2.5 m/5.0 m	72	182.5 m	N 350° E	23.0 m
TM4	5.0 m	24	115.0 m	N 340° E	22.5 m
TM5	2.5 m	48	117.5 m	N 330° E	23.0 m

Table 1. Length, interelectrode spacing, electrode number and maximum depth below the modern topographic surface reached by each TM profile are listed.

Drilling of the cores was performed without the use of circulation fluid to better preserve sedimentary structures, textures, and fabric. Macroscopic characters of the core sediment were defined by a caliper for granules and pebble-size clasts while the grain-size of sand was determined optically by using visual comparison charts. These also allowed to assess clast rounding, sphericity, and sediment sorting. The sediment color was determined by means of the Munsell Soil Color Charts [35], and the thickness of sediment units was defined according to [36]. Selected samples were also analyzed and statistical parameters were even calculated using standard methodologies [37, 38]. Graphic stratigraphic logs were plotted of each drill-core examined.

The sediment cores and logs that constitute the geostratigraphic archive for the study area are stored at the Laboratory of Applied Researches of the Soprintendenza Archeologica at Pompeii.

The AMS radiocarbon analysis reported by Senatore et al. [18] is used to insert the identified units in a chronostratigraphic framework. The base map of **Figures 3** and **7** is an official georeferenced topographic map produced at 1:5000 scale.

The geological interpretations were integrated with the available archeological information.

3. Results

3.1. Stratigraphic units to northwest of Pompeii

The stratigraphic units, identified in the boreholes carried out northwest of Pompeii (**Figure 3**), are composed mostly of volcaniclastic deposits both in primary deposition (eruptive products) and secondary deposition (reworked deposits). Their thickness is from centimeters to several meters, with a highly variable lateral distribution.

Seven stratigraphic units have been identified in a section trending northeast-southwest (from A to B in **Figure 3**). From the topographic surface, they are (**Figure 4**):

- Uc1 represents the deposition following the AD 79 eruption and consists of volcaniclastic sand with brown clay matrix. Plant matter, especially roots, are present. In the upper unit, the sediments are mixed with material linked to the human activity, mainly fragments of brick and pottery. The thickness ranges from few centimeters to 3 m. The basal contact is always sharp.

- Uc2 represents part of the AD 79 eruption deposits and consists of two layers of pumice. The first one is composed of gray pumice, several centimeters in diameter in a volcaniclastic fine sand matrix. The second one is composed of white pumice, few centimeters in diameter. In some cases, the gray and white pumice are mixed to form a single layer. The thickness of the unit is from about 2 m to about 5 m.

- Uc3 represents the Roman and pre-Roman deposits and consists of brown coarse to fine well-rounded volcaniclastic sand. Rounded pumice (few centimeters in diameter) and lapilli clasts, and angular and subangular fragments of artifacts and of animal bones are found in this unit.

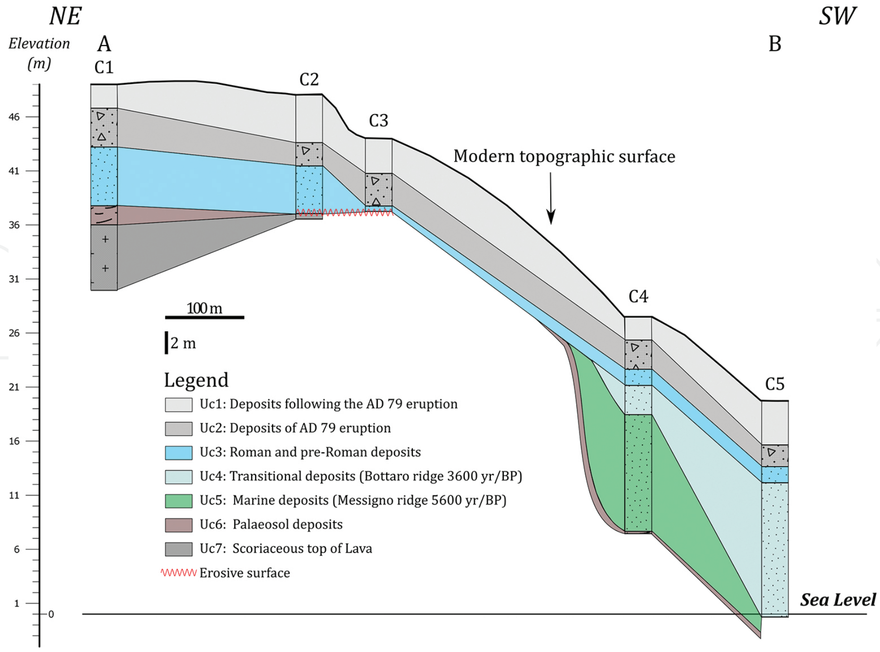

Figure 4. Cross section (A and B) showing the stratigraphic architecture of the units that constitute the northern Pompeii succession (position in **Figure 3**).

The character of the Uc3 deposits allows to define a fluvial channel and the Uc2 deposits as a channel fill while the Uc1 deposits cover the previous units hiding the preexisting morphologies.

- Uc4 is constituted by dark gray, coarse to very fine volcaniclastic deposits with rounded centimetric pumice and lapilli clasts. These deposits are found in the C5 borehole, showing a thickness of about 5 m, and in the C4 borehole with a thickness of 12 m. They are typical of transitional environment and have been correlated to the well-known Bottaro ridge deposits [18], cropping out southwest to the archeological site. They represent an ancient shoreline with radiocarbon age of about 3600 yr/BP [39].

- Uc5 is composed of dark yellow, silty clay deposits with centimetric, rounded, gray pumice and lava clasts. They are found in the C4 borehole with a thickness of about 10 m. The character of the sediment, well known in other analyzed boreholes, allows the correlation to a marine environment linked of the Messigno ridge deposits [18, 23], cropping out southeast to the archeological site inland to the Bottaro ridge. Messigno ridge also represents an ancient shoreline with radiocarbon age of about 5600 yr/BP [39].

The Messigno and Bottaro ridge deposits are found at higher elevations than those with the same age studied in other tectonically stable areas. Significant Holocene ground movements at Somma-Vesuvius area are in fact recorded [40–42].

- Uc6 is constituted by very dark brown, silty clay deposits with weathered white pumice clasts, some millimeter in size, and some remains of roots. This layer is a paleosol and is present at the base of C4 borehole below the Messigno ridge deposits with a thickness of several centimeters, in the C1 borehole at the base of the Uc3 unit, and on the top of the Uc7 unit with a thickness of 2 m. This is lacking in the C2 and C3 boreholes, probably due to an artificial excavation.

- Uc7 is represented by the scoriaceous top of the lava layer that constitutes a morphological high on which the ancient city was built. This unit is found in the C1 borehole where, below the scoriaceous layer, the lava is present; while in the C2 borehole, the scoriaceous layer is just reached. The Uc7 unit is considered the base of the northwestern Pompeii succession.

3.2. Electrical resistivity tomography profiles

Four electrical resistivity tomography (ERT) profiles were acquired to obtain additional information on the subsurface paleogeography based on the water content in the sediment referring to the resistivity values that are from about 10 ohms/m, indicating high humidity up to water presence in the sediment, to 2900 ohms/m, indicating complete absence of water.

The profile trend is NNW-SSE (**Figure 3**). **Table 1** shows the length, interelectrode spacing, electrode number and maximum depth below the modern topographic surface reached by each TM profile.

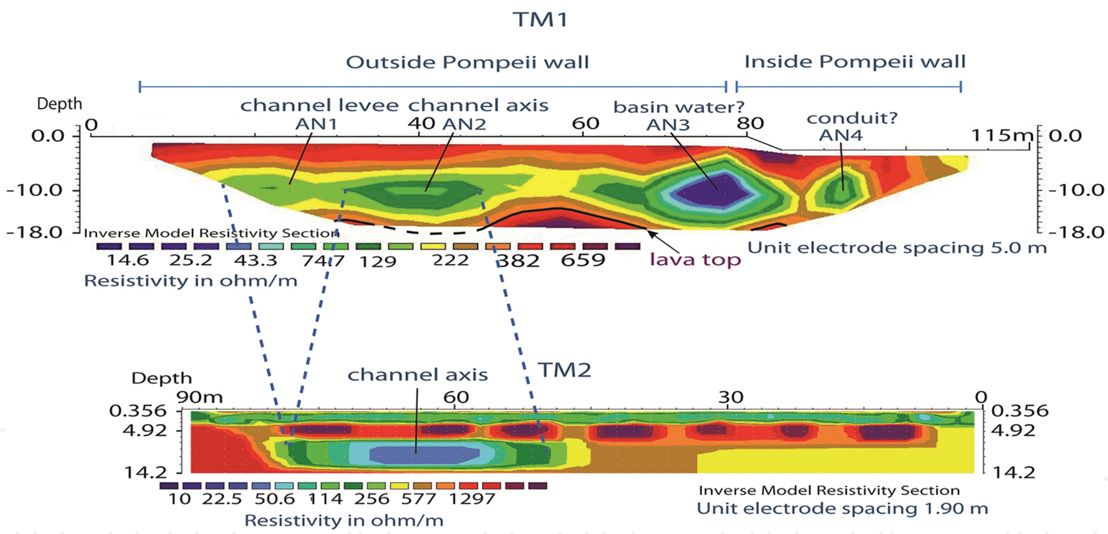

Figure 5. Electrical resistivity tomography (ERT profiles; location in **Figure 3**) showing the characters of the artificial canal (see text for detail) (TM1 modified from [18].

The TM1 profile shows two resistivity anomalies (AN1 and AN2), with resistivity values ranging between 222 ohms/m and 129 ohms/m (**Figure 5**). These anomalies are interpreted, respectively, as the levee and axis of an artificial canal since this profile was performed on the unexcavated dig-front of an archeological excavation outside of Capua Gate (**Figure 2**) and made to examine the subsurface beneath the 79 AD eruption deposits [18]. The archeological excavation has revealed the presence of an artificial canal, which is in the coincidence of the anomaly AN2 on TM1 of **Figure 5**, as there is a close match with regards to both its position relative to electrodes and its depth beneath the present topographic surface. The AN1 on TM1

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represents the levee of the canal (see **Figure 6** in [18]). Resistivity values ranging between 382 ohms/m and 659 ohms/m, recorded at the base of profile, are interpreted as the top of the lava layer on which the channel is excavated and Pompeii was built.

Two other ERT anomalies are identified on TM1 (AN3 and AN4 in **Figure 5**) that have generally circular shapes, one of which (AN4) occurs in the archeological area that has not yet been excavated. Anomaly AN3, positioned near the wall, presents a series of concentric resistivity values, which range from 129 ohms/m at the periphery to 14.6 ohms/m at the center of the feature. These values suggest the presence of sediments characterized by high humidity or, possibly, water content. The characteristics of anomaly AN3, the base of which is at the same depth as that of the channel mapped in the excavation, have suggested an anthropogenic structure, probably linked to the water supply distribution to Pompeii [18]. Anomaly AN4, with circular profile and smaller size than AN3, has resistivity values at its center comparable to those of the channel (222 ohms/m and 129 ohms/m). This is interpreted as a smaller channeling feature such as a duct or conduit that was probably related to the city's water distribution system as well [18].

The other four ERT profiles were carried out to trace the path of the artificial canal excavated to carry water to the city, starting from the wide meander of the stream flowing from the inland mountains. In the TM2 profile (**Figure 5**), the canal is identified between electrodes 50 and 76 and between about 7 m and 14 m in depth while the resistivity ranges from 10 ohms/m to 114 ohms/m. In the TM3 profile, the canal is identified between electrodes 70 and 85, and at depth from 5 m to about 20 m. The resistivity ranges from about 50 ohms/m to 114 ohms/m. In these two profiles, the shape of the channel is unnatural, clearly artifact, to allow the flow of the water in the canal by gravity.

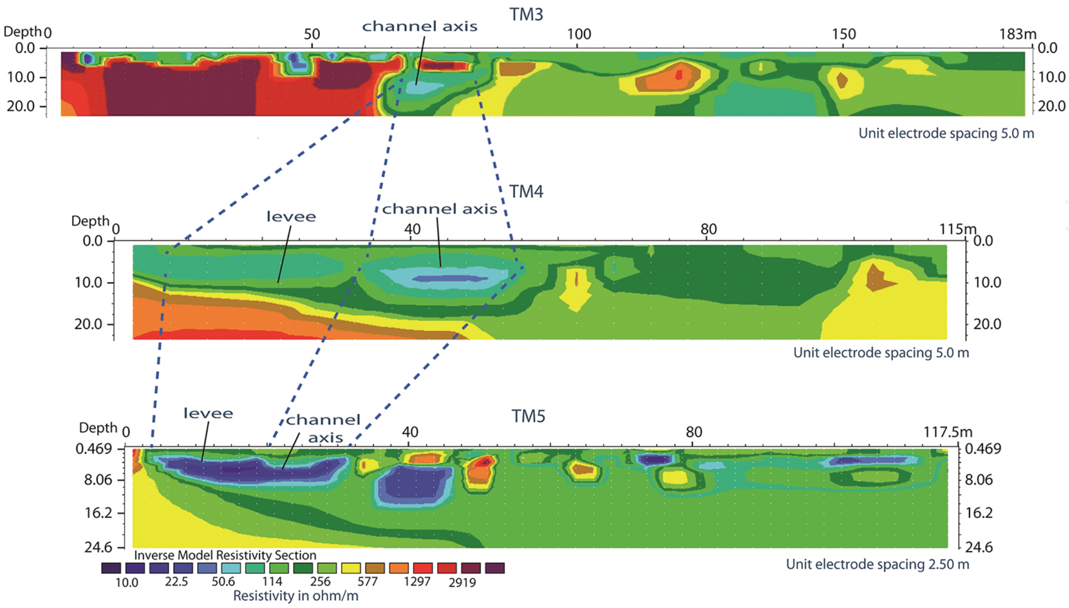

Figure 6. Electrical resistivity tomography (ERT profiles; location in **Figure 3**) showing the characters of the artificial canal (see text for detail).

TM4 and TM5 profiles show the canal between electrodes 35–55 and 25–32, respectively, where the depth is from about 2 m to 10 m (**Figure 6**). The resistivity values are between 10 ohms/m and 114 ohms/m.

Figure 7 shows the path of the canal, which develops from Capua Gate, where, according to [18], a water basin and a conduit, supplied water to Pompeii. The water, entering the city, was then distributed utilizing the gravity. In fact, as stated before, the elevation is greater in this area, and it gradually decreases toward Stabia Gate and the archaic part of the city on the edge of which, the flowing water activated the water wheels (**Figure 2**). The channel path continues toward Vesuvius Gate, touching a farm (Villa Rustica Suburbana) with a foundry [43, 44] and then toward Villa of Mysteries.

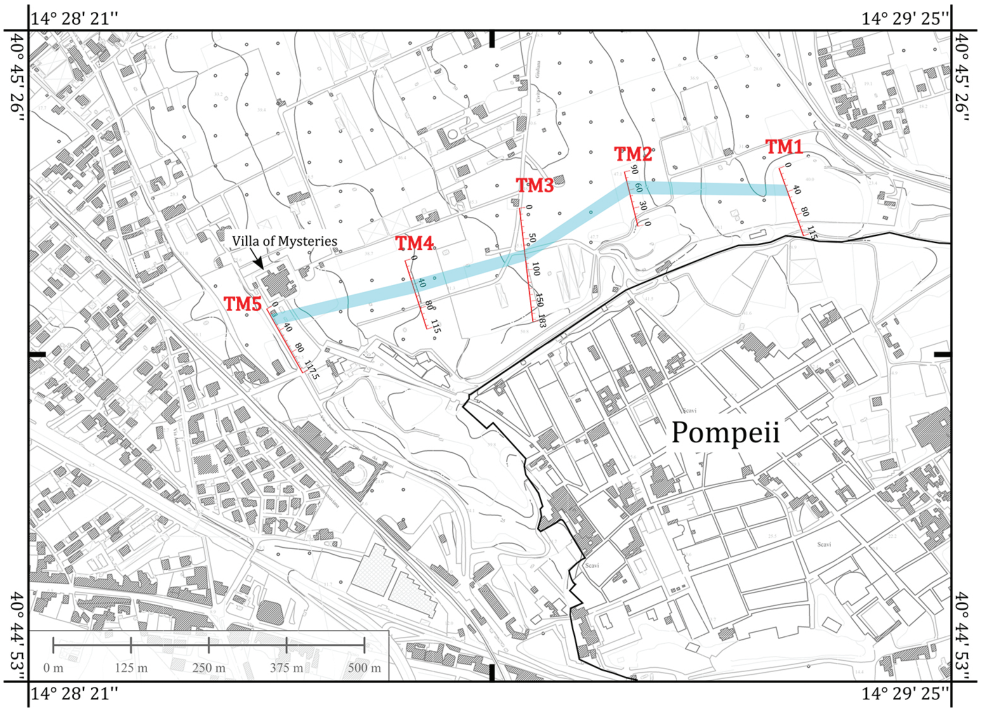

Figure 7. Reconstruction of the path of the artificial canal made by means of ERT profiles and sediments collected in the C boreholes.

The low-resistivity values recorded on the ERT profiles, in connection with the canal, indicate sediment characterized by high humidity up to contain water. They suggest that the canal incision, even today that it is filled by sediments, represents a preferential path for the water flow below the topographic surface.

3.3. Mass gravity flow units

Three flow units, termed Uf1, Uf2, and Uf3 (**Figures 8** and **9**), from the lava base of the succession upward, have been identified in the boreholes carried out the city and the surrounding area (**Figure 3**). Root structures at boundaries between the units indicate that some time has elapsed between the deposition of different mass-flow events.

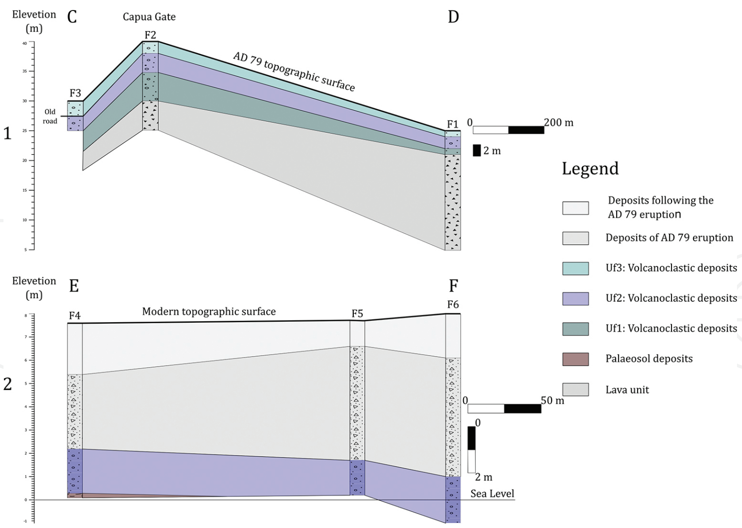

Figure 8. Cross sections: (1) through the flood units (F) to north of Pompeii; (2) through the flood units to south of (position in **Figure 3**). Capua gate is the place where the water enters into the city (position in **Figure 2**).

- Uf1 is composed of massive volcaniclastic deposits with rounded volcanic clasts, rounded to angular fragments of animal bone and plant matter. The unit has a thickness from 1 to 5 m, and rests on the lava upon which Pompeii was built (F1 and F2 in **Figure 8(1)**). The radiocarbon-dated animal bone fragments provided a calibrated age of 764 years BC [18].

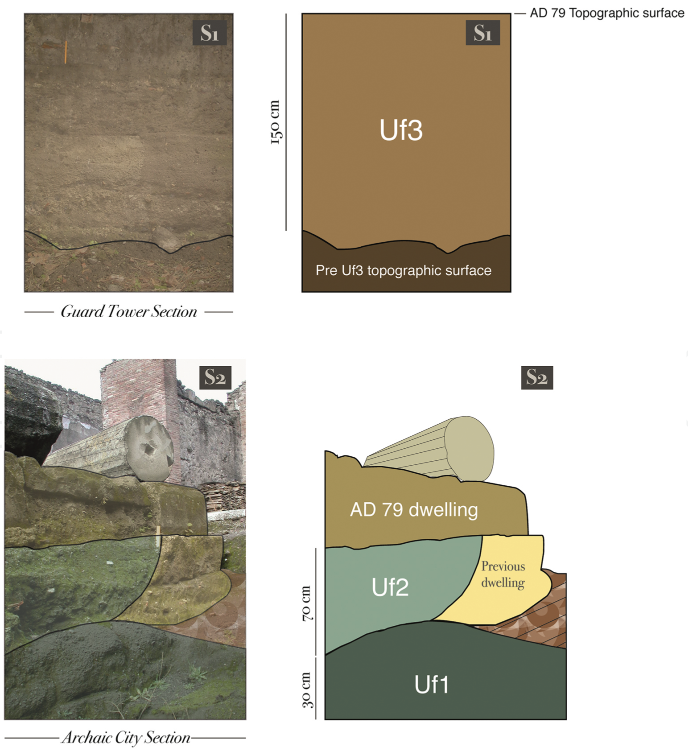

Figure 9. The flood units cropping out in the archaeological excavation and laterally to the Guard Tower door (see text for details).

- Uf2 is identified within and outside city walls (**Figure 8**(**1** and **2**)), and is constituted of massive volcaniclastic deposits, mainly structureless, or with some thinner cross or planar lamination at the base unit. The matrix is prevalent, with clasts randomly oriented, or, some, may show imbricate structures. The clasts are represented by rounded volcanic clasts and calcareous pebbles, rounded to angular fragments of brick and ceramics, plaster, animal bone, and plant matter. This unit has an average thickness of ~2 m. In the archaic city, the Uf2, between two construction levels, incises Uf1 and covers an older building level (S2 in **Figure 9**). It can be reconstructed that the older dwelling, built upon Uf1, has been damaged by the Uf2 deposits. Subsequently, a new structure was built at a higher elevation upon the Uf2 and was used until its destruction by the 79 AD eruption.

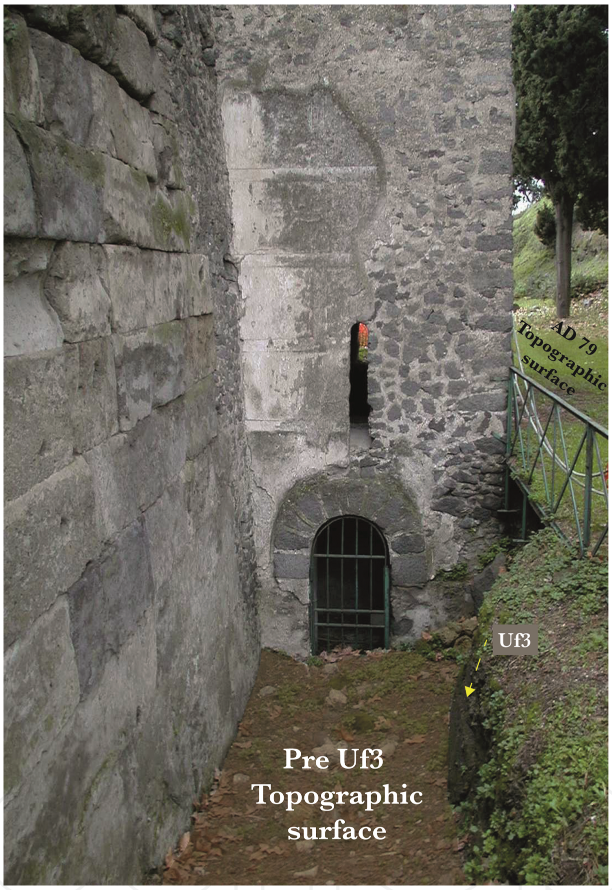

Figure 10. Guard Tower (position in **Figure 2**): the door is below the AD 79 topographic surface and on its left the Uf3 section crops out (see S1 in **Figure 8**).

- Uf3 is composed of matrix-prevalent volcaniclastic deposits with randomly distributed clasts that commonly comprise rounded volcanic clasts and rounded to angular fragments of pottery, plaster, animal bone, and plant matter. These deposits have an average thickness of ~1 m, occurring along the northern city wall (F1 and F2 in **Figure 8(1)**). In F3, Uf3 buries an ancient road trending from the city toward Villa of the Mysteries (**Figures 3** and **8(1)**). Section S1 (in **Figure 9**) is located laterally to the door of a Guard Tower (**Figures 2** and **10**) and shows the Uf3 character. The Guard Towers were added to the city wall during the second century BC

[45]; the tower doors, openings at their base, nowadays, occur beneath the topographic surface of the AD 79 (**Figure 10**). They have been buried by Uf3 deposits and were used until the AD 79 eruption after the removal of the Uf3 material. The radiocarbon-dated animal bone gave a calibrated age of 170 years BC [18].

4. Conclusive remarks

The sediment characteristics of the three Uf units indicate that mass gravity mechanisms, especially debris flow, were the dominant processes responsible for their transport, and the two younger units had flooded Pompeii causing severe damage to the city. The volcaniclastic sediment with matrix-supported clasts likely originated as slope collapse and avalanche displacement from the flanks of calcareous terrains of mountains to the NE (Pizzo D'Alvano area; **Figure 1**). During landslides, slumped masses of unconsolidated material can be transformed to high-concentration debris flows as has been recorded in volcanic areas elsewhere [46]. Confined within downslope-trending depressions, such as channels, flows can travel considerable distances toward lowlands by expanding in volume during transport through a bulking mechanism that involves incorporation of additional sediment and water [47]. In the studied area, these deposits were released from hyperconcentrated slumps and debris flows that had incorporated sediment and water during the course of downslope transport in the fluvial channel. The first flood event, which had not occurred through the canal, took place in 764 BC, before the foundation of the city was built [18], and has affected a wide area of the Sarno Plain.

The available data allow to reconstruct the hypothetical phenomena that can be occurred in a temporal sequence during the emplacement of the second and third flood events, linked both to the canal built by the Samnitic population for water supply [18]. Therefore, the flow, in the fluvial channel, reached the great bend to north of Pompeii. Hence it was channeled in the artificial canal and continued its course within it. In the proximity of the Capua Gate, the canal width being narrower than that of the fluvial channel, the flow overflowed its banks thus flooding the city. This event caused severe damage in the archaic city (S2 in **Figure 9**). According to [18], this flood could have occurred during the fourth century BC. The third flood event, which took place in 170 BC [18], whose sediments were found only in F1, F2, and F3 boreholes (**Figure 8(1)**) and in S1 section (**Figure 9**), seems to have caused severe damage only in the northern part of the city.

At the Capua Gate inside the city walls, a duct was discovered under the first floor of a building [32]. This feature that was filled with sediment of the Uf3 unit may represent the extension of the duct highlighted by the anomaly AN4 in the TM1 ERT profile [18]. The sediment of the Uf3 unit was also piled against the entrance door of the building discovered at Capua Gate. According to [18], it is proven that at the time of the AD 79 eruption, the building and the duct below the floor were no longer used. It seems that after the mass-gravity flood event that had deposited the Uf3 unit, the water distribution system at the Capua Gate had to be abandoned due to its danger for the city. Hence, a new water supply system had to be organized. In fact, in 80 BC, a circular water basin was built close to the Vesuvius Gate and was connected to an aqueduct originating from the mountains northeast of the town named Avella (Avella Aqueduct [48]). The circular basin was afterwards covered (Castellum aquae, **Figure 3**) and was connected to the new Serino Aqueduct, in 20 BC [49–51]. This last water system was in use until the final demise of the city because of the Vesuvius eruption.

In conclusion the geological data prove that the first system for water supply caused floods that, in turn, caused severe damage to the city. Hence, the water, usually as resource, in some cases can turn into geohazard.

Acknowledgements

Funding was provided by Ministero Università e Ricerca Scientifica (Pon Project 12232; MRS) and Università degli Studi del Sannio (FRA Projects; MRS). MRS is grateful to the staff of the Laboratory of Applied Researches of the Soprintendenza Archeologica di Pompei: Luigi Buffone, Antonio Stanpone, and Vincenzo Di Martino. In memory of Annamaria Ciarallo, the first director of the Laboratory of Applied Researches.

Author details

Maria Rosaria Senatore*, Maddalena Falco and Agostino Meo

*Address all correspondence to: senatore@unisannio.it

Department of Science and Technology, University of Sannio, Benevento, Italy

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